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STATUS, FUTURE TRENDS IN SENSOR TECHNOLOGY

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SCIENCE & TECHNOLOGY

JAPAN

STATUS, FUTURE TRENDS IN SENSOR TECHNOLOGY

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Temperature Sensors

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[Article by Kosuke Takeuchi, Functional Materials Laboratory, Research and Development Headquarters, Sanyo Electric (Inc): "Temperature Sensors and Trends in Their Development"]

[Text] 1. Introduction

Temperature is the most basic physical quantity in our lives and in all sorts of fields, such as experiments of various types. Therefore, as society has developed, measurement of temperature has become increasingly important, and has become indispensible in many such fields as manufacturing, industry, medical treatment and disaster prevention. In particular, accompanying the development of microprocessor technology in recent years, the need for temperature sensors that output such electric signals as voltage and current has expanded for the purpose of processing the signals as required at the same time that one detects the temperature by means of the sensor.

The history of the development and practical application of temperature sensors goes back farther than that of other sensors. The material values of all sorts of substances are expressed as a function of temperature, so there are also many types of sensors, and their measurement-principles are also varied. Here, I will first present the basic principles of temperature measurement and the classification of temperature sensors; next, I will describe the present status of temperature sensors, and, finally, I will describe recent development-trends of temperature sensors.

2. Basic Principles of Temperature Measurement

Table 1 shows heat-phenomena related transformation principles and effects, and examples of sensors which have been developed by utilizing these principles and effects. Next, I shall discuss the special characteristics of these transformation principles and effects.

Table 1. Heat-Phenomena Related Transformation Principles and Examples of Sensors

Transformation Principles	Examples of Sensors
Thermoelectric effect	Thermocouple, thermopile
Pyroelectric vidicon	Pyrovisicon
Thermal expansion	Mercury thermometer, goraycell
Temperature characteristics of resistance	Thermistor, resistance thermometer
Temperature characteristics of PN junction	Transistor thermometer
Temperature characteristics of piezoelectric constants	Mercury thermometer
Ferromagnetism - paramagnetism phase transposition	Temperature-sensing reed switch
Temperature characteristics of nuclear quadpole resonance	NQR thermometer
Josephson effect	
Thermal noise	Thermal noise thermometer
Thermal radiation	Radiation thermometer

(1) Thermoelectric Effect

When one constructs a closed circuit from two types of metal wire, and maintains their juncture points at different temperatures, one produces thermoelectricity which corresponds to the temperature difference. The same characteristics can be obtained in regard to this thermoelectricity if the element wire is decided on.

(2) Pyroelectric Effect

If the amount of spontaneous polarization of a ferroelectric substance changes according to the temperature, an electric charge is produced in the direction of polarization. The amount of this charge corresponds to the size of the temperature change of the ferroelectric substance. When the temperature reaches a stable state, this electric charge is neutralized to a floating charge in the air, and cannot be detected.

(3) Resistance Temperature Characteristics

The characteristics of the electrical resistance of metals are the same if the material is the same, so reproducibility is easily obtained. Platinum resistance thermometer bulbs, in which platinum is used, are

used in the lPTS 68 international practical temperature scale, and are also prescribed in the JIS.

The resistance-temperature characteristics of semiconductors changes according to their composition, and thermistors which have been given large temperature characteristics can do high-resolution measuring.
(4) Temperature Characteristics of PN Juncture

The voltage between the base emitters of silicon transistors has a temperature coefficient of - 2 m V /degrees Centigrade. The theory of this temperature dependency has been elucidated, so it is possible to seek the absolute temperature theoretically.

(5) The Temperature Characteristics of NQR [nuclear quadpol resonance]

This is something that utilizes the effect by which the resonance absorption frequency in the nuclear quadpole resonance phenomenon, which derives from the Cl^{35} atom nucleus in $KClO_3$ (potassium chlorate), decreases along with a rise in temperature; the temperature and the resonance absorption frequency are determined unmistakably, so if one seeks this relationship once in advance there will be no need for revision. The temperature-dependence of the NQR frequency is shown in Figure 1.

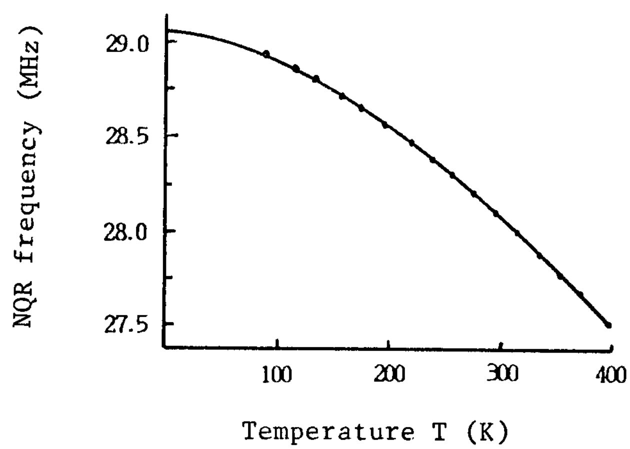


Figure 1. Temperature Dependence of the NQR Absorption Frequency of the Cl^{35} Nucleus

(6) Temperature characteristics of thermal noise

Because of the thermal motion of electrons, a fluctuation of the electric potential, called thermal noise, is produced at both ends of a resistor. This thermal noise is also called Johnson Noise [English

given], and it has been elucidated theoretically by Nyquist. Thermal noise is expressed in the manner of following formula.

$$\overline{e_n^2} = 4\ K\ T\ R\ \text{delta}\ f$$

K: Boltzmann's constant, T: absolute temperature
R: resistance value, delta f: width of the observation band of the noise

In thermal noise, the theoretical thermodynamic relationship between temperature and voltage is clear, so measurement of a wide temperature range is possible without depending on sensor materials. There is no change with the passage of time, either.

(7) Thermal radiation

It is possible to measure temperature without contact by utilizing the thermal radiation that is radiated from an object's surface.

As shown in Figure 2, this thermal-radiation energy has a temperature distribution that corresponds to each temperature, and the higher the temperature becomes, shorter the wavelength to which the peak frequency shifts. When measuring temperatures of less than 1000 K, infrared sensors are used in order to detect infrared light.

Infrared sensors are classified into the heat type and the quantum type: the heat type uses the heat phenomenon derived from the heat-ray action of infrared light, and the quantum type uses the photoelectric effect.

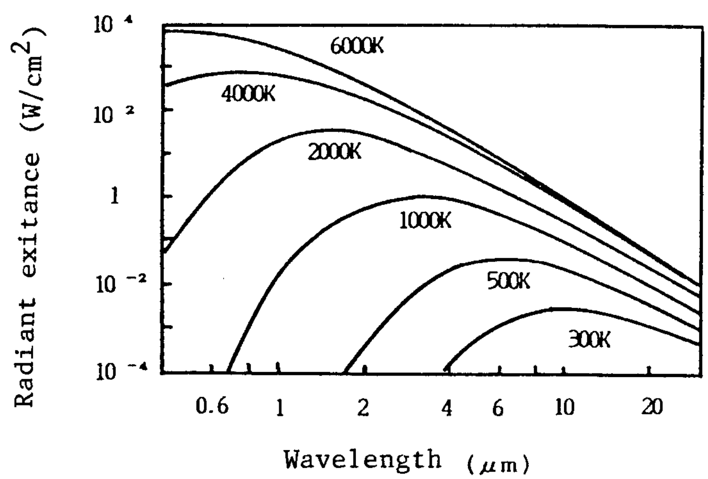


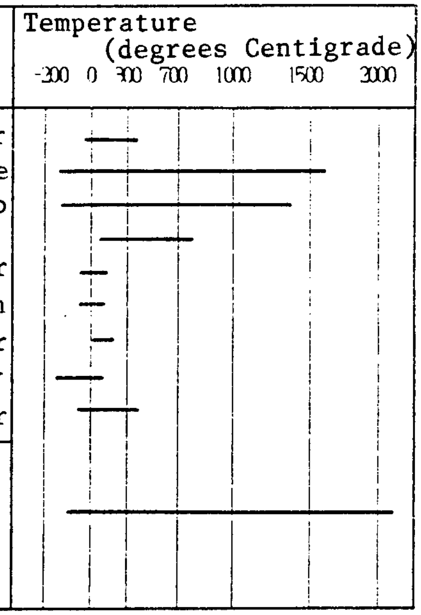
Figure 2. Wavelength Distribution of an Object's Temperature and Radiant Energy

3. Classification of Temperature Sensors

If one classifies temperature sensors according to their method of use, it is possible to divide them roughly into two types. One is the contact type, which detects by making direct contact with an object; the other is the non-contact type, which uses the infrared light emitted from an object. Table 2 shows the classification of temperature sensors, and the temperatures which they measure.

Table 2. Classification of Temperature Sensors, and the Range of Temperatures Measured

	Sensor Classification
Contact Type	Liquid thermometer
	Thermocouple
	Resistance bulb
	Thermistor
	PN-juncture type temperature sensor
	Temperature-sensing reed switch
	Crystal temperature sensor
	NQR thermometer
	Thermal noise thermometer
Noncontact Type	Radiation thermometer



The structure of contact-type sensors is simple, and they are most widely used at present. The structure of noncontact type sensors is complicated because of such things as correction being necessary for measurement of the absolute temperature, but practical application has progressed rapidly of late. When using this kind of temperature sensor it is important to select the optimal sensor for what one is measuring by studying the points presented below.

{Items Necessary for Sensor Selection}

(1) Temperature range to be detected
(2) Sensitivity and accuracy
(3) Speed of response
(4) Dispersion of characteristics
(5) Shape and size

(6) Reliability of such things as strength, heat resistance and alteration with the passage of time.
(7) Cost

4. Present Status of Temperature Sensors

According to statistics on production of sensors in general in Japan in FY85, the monetary value of production exceeded=Y250 billion, and the number of units produced reached 2 billion. Their application covered various fields, such as home electric appliances, automobiles and disaster prevention. Application to the home electric field accounts for a particularly large proportion, and approximately 400 million sensor units are being used.[1)]

Temperature sensors account for approximately 20 percent of the sensors that are being used in home electric appliances, and, as shown in Table 2, they are now used in most of the electric appliances currently used in the home.[2)] In these products temperature sensors have become an important factor in winning in competition for markets, making products very attractive by such things as making them convenient, developing multiple functions and helping to conserve energy and guarantee safety. Therefore, there is great demand for small, inexpensive sensors.

Conversely, in such fields as process control and environmental instrumentation, in which sensors play the main role, sensors are being demanded which measure with great accuracy and have superior resistance to the environment.

5. Trends in Development of Temperature Sensors

As temperature-sensor needs have become more diverse, demand for a change to higher performance and higher functions in sensors has begun to grow stronger. Such things as greater reliability, higher performance and lower price are being demanded of existing sensors; and for new sensors, a greater number of functions, intelligence, integration, and sensors based on new principles are being demanded. All sorts of facilities are vigorously carrying on R&D concerning this. I will give examples of sensors the development of which is currently being promoted, and will discuss their special features and so on.

5-1. A Change to Thin Film

(1) Thin-Film Thermistor

Silicon carbide (SiC) is a superior material in terms of resistance to heat and corrosion, but processing was difficult because bulk crystals are very hard. However, an SiC thin-film thermistor was developed by the RC sputter method. As shown in Figure 3, this SiC thin-film

thermistor differs from conventional thermistors, so it has become possible to measure a wide range of temperatures.

Table 3. Status of Sensor Use in Home Electric Appliances

	Microwave ovens	Ovens	Automatic rice cookers	Refrigerators	Room air conditioners	Electric leg warmers [kotatsu]	Hair dryers	Clothes dryers	Electronic mosquito killers	Gas water heaters	Electric blankets	Toasters	Irons	Kerosene appliances
Pressure type		△		◎	○			△		○				
Bimetal		○	△		○	◎	△	◎			△	◎	◎	○
Thermocouple										○				
Thermistor	◎	◎	◎		◎	○	△	○				△	△	○
PTC			○		△	△	○	○	◎			△		
Thermoferrite			◎											
Organic temperature-sensing elements											◎			

◎ Many being used

○ Being used

△ Being used by some people

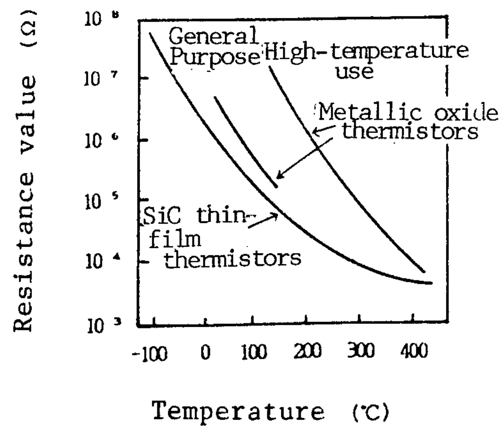


Figure 3. Temperature Ranges Measured by the SiC Thin-Film Thermistor and Conventional Thermistors

Furthermore in the material of conventional thermistors, too, by turning it into thin film, the homogeneity of its composition rises and dispersion of the resistance value declines, so it is possible to raise the performance.

(2) Thin-Film Platinum Temperature-Measuring Resistor[4]

Platinum temperature-measuring resistors require precision hand-work, and material costs are also high, so they were expensive. They were changed to thin film in order to enhance their suitability for mass production, and a reduction in cost is being realized without lowering their special qualities too much.

5-2. Integration, Development of Intelligence

(1) IC Temperature Sensors[5]

In general sensor signals are small, and their processing is not a simple manner for anyone other than a specialist. Therefore, development of intelligence that will convert sensor signals into signals that are easy for users to process, and then output them, is desired.

IC temperature sensors use the special voltage-temperature characteristics of PN juncture, and simultaneously, by the Si process, they are preparing a circuit which processes the sensor signals. It is arranged that output is in proportion to the absolute temperature, so it is easy to utilize in control circuits and so on.

(2) IR-OPFET[6]

There is an element called an IR-OPFET, which manufactures on a silicon MOSFET a pyroelectric-type infrared sensor for measuring temperature, without contact, by means of the infrared rays radiated from an object. Its structure is shown in Figure 4. $PbTiO_3$ pyroelectric material is

placed on the FET gate section by the RF sputtering method; it can detect infrared light because when infrared light strikes the pyroelectric material, the drain current changes because of generation of an electric charge based on the pyroelectric effect.

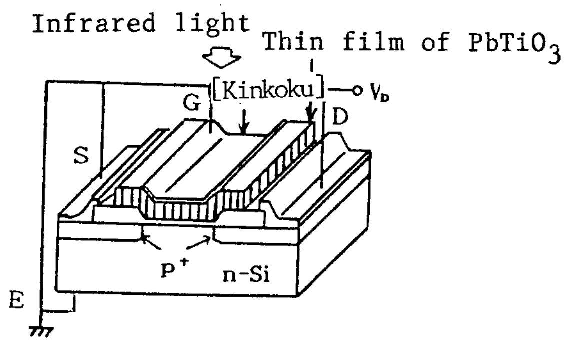


Figure 4. Structure of the IR-OPFET

5-3. Hybridization

(1) Pyroelectric Infrared Sensors Built Into Choppers[7)]

Since pyroelectric infrared sensors are differential sensors that generate output by temperature changes caused by infrared light, it is necessary to make the infrared light intermittent in order to obtain output continuously.

Hitherto, the infrared light was made intermittent by rotating a metal chopper by means of a motor, but a minute pyroelectric infrared (non contact temperature) sensor has been developed which brings together the sensor part and the chopper part in the same package by constructing an infrared chopper out of a bimorph oscillator and a metal slit . This sensor has been reduced in size to approximately 1/20th the size of the existing temperature-measuring system, which used a motor. The structure of this sensor is shown in Figure 5.

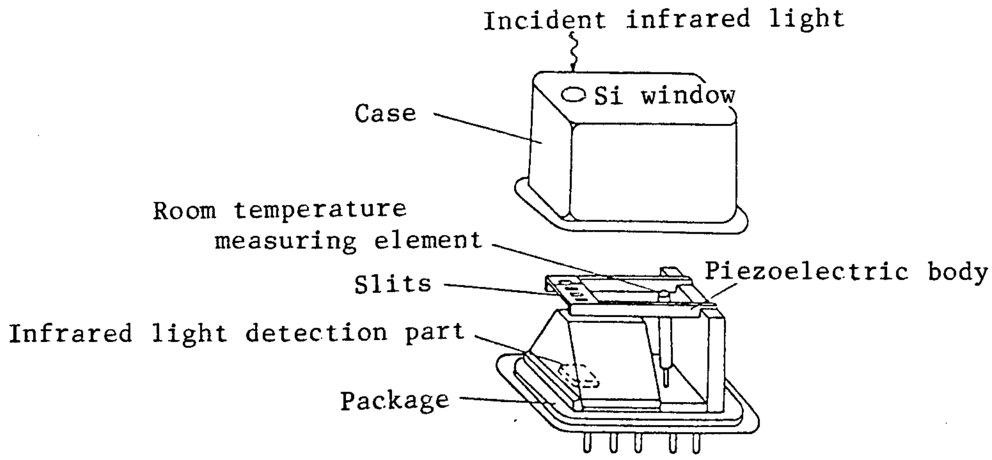


Figure 5. Structure of the Minute Modulation-Type Pyroelectric Infrared Sensor

5-4. Improvement of Performance

(1) Elastic Surface-Wave Temperature Sensor

This is something which, in the same way as crystal temperature sensors, detects temperature from changes in the oscillation frequency by using the temperature dependence which is a special characteristic of piezo electricity. It is composed of a surface-wave delay-element and a feedback amplifier, and has a structure like that shown in Figure 6. In ones with substrates of $LiNbO_3$, the temperature-detection characteristics are 8.8KHz/degrees centigrade, a level three times that of crystal. Furthermore, frequencies are measured accurately with comparative ease, so application to other sensors is also anticipated.

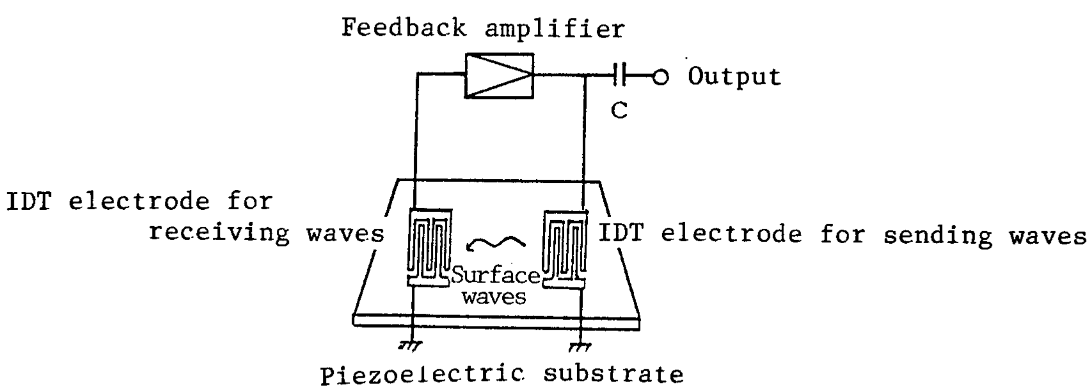


Figure 6. Structure of an Elastic Surface-Wave Temperature Sensor[8)]

5-5. Sensors That Use New Principles

(1) Optical Fiber Temperature Sensors

These are temperature sensors that use optical characteristics; there are ones which utilize optical fiber as photo-transmission circuits and ones which utilize the optical fiber's own temperature characteristics.

In the former, light emitted from the light-source part is transmitted to the sensing part by fiber, undergoes a change of state because of temperature, and comes back to the light-receiving part. As one example, there are such things as a sensor that measures temperature by attaching GaAs, the light-absorption volume of which changes according to temperature, to the tip of the optical fiber, and detecting changes in the volume of light that passes through.[9)]

In the latter, there is one that uses two strands of optical fiber, and, using one for measuring temperature and the other for reference, utilizes interference of the outgoing light from the two strands. With temperature sensors like the one shown in Figure 7, when the temperature changes, the difference in the refractive index of the two optical paths changes, so a phase difference is produced in the light that is propagated. The interference stripe moves because of this, and the temperature is measured based on the amount of movement.[19)]

Optical-fiber temperature sensors have the special characteristic of "not being influenced by magnetic noise," and "having excellent qualities as insulators," so it seems to me that their application to fields in which it is difficult to use existing sensors will advance.

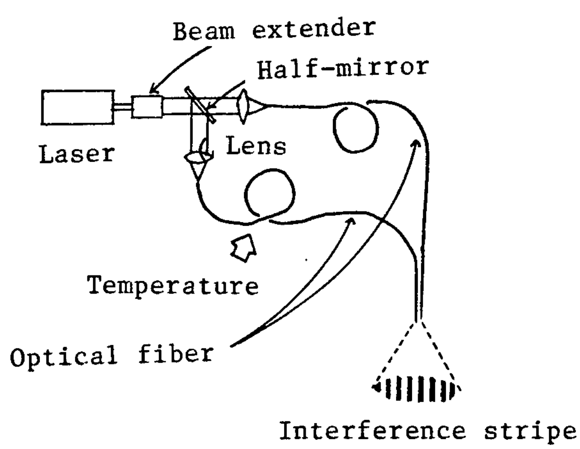


Figure 7. An Optical-Fiber Temperature Sensor

6. Conclusion

I have presented a summary of temperature sensors, and discussed trends in future development. It is something said of sensors in general, but in order for sensors to be applied to still more fields in the future, it will be necessary to lower prices and increase reliability, not to mention heightening functions. Therefore, not only R&D of new principles and new materials, but development of such peripheral technologies as application technology and production technology are desired.

Silicon Magnetic Sensors

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[Article by Kazusuke Maenaka and Tetsuro Nakamura, Faculty of Electric and Electronic Engineering, Toyohashi University of Technology: "Present Status and Future of Silicon Magnetic Sensors"]

[Text] Introduction

Magnetism has been in continuous use from an early time as a medium for the purpose of detecting such things as position, angle of rotation, current and electric power. Today, when control of a high degree has developed based on microprocessors, the scope for application of magnetism is growing wider and wider, so the emergence of still more diverse, higher-function magnetic sensors is hoped for as one part of control systems.

At present, the following kinds of things exist as well known magnetism detection devices.

1. MR Elements: Elements that use the magnetoresistance effect of thin films of ferromagnetic materials like Ni-Co.

2. Hall Elements: Elements that use directly the Hall effect, which is produced in semiconductors of InAs, InAsP, Ge, InSb, GaAs or Si and so on.

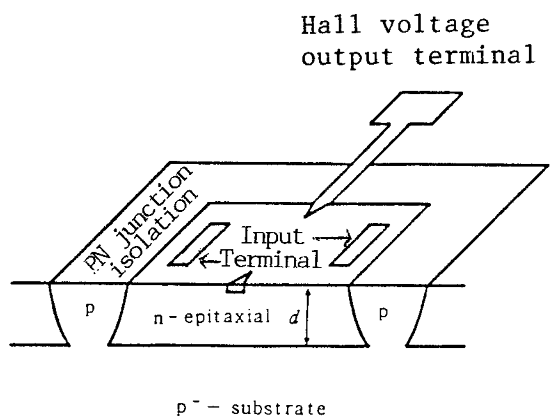

Figure 1. Hall Element Manufactured by a Bipolar Process

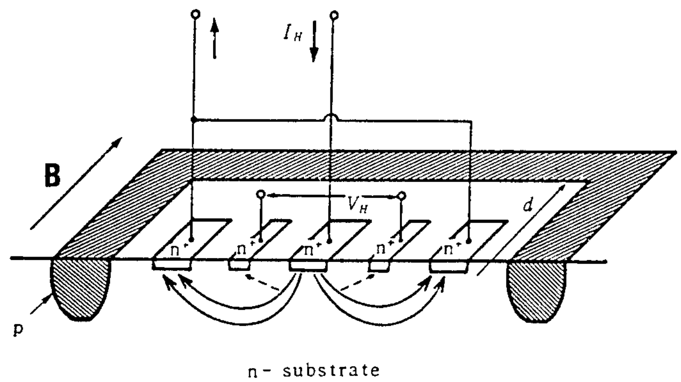

Figure 2. C-MOS Vertical Hall Element

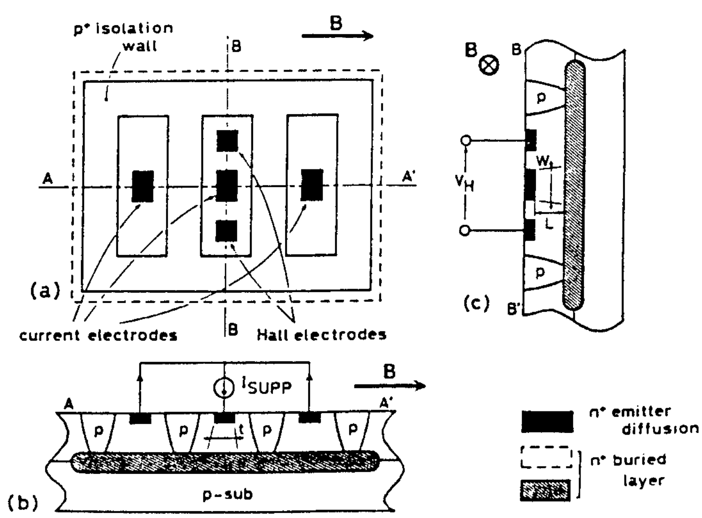

Figure 3. Bipolar Vertical Hall Element

3. Magnetic Transistors: Magnetism-detection elements that possess the structure of transistors, and use the Hall effect and carrier deflection indirectly. Typically, they have two collectors, and make the differential current of the collectors' currents their detection output.

4. SQUID: These are magnetism-detection elements of superconductive metals which use Josephson junctions, they are highly sensitive elements that can detect even a magnetic field on the order of 10^{-14}. They are used in measuring biomagnetism and so on.

5. Other: There are many kinds of magnetism-detection elements: the pick-up coil (magnetic head), which uses magnetic induction directly and is still used widely, optical fiber magnetic sensors that use the Faraday effect, sensors that utilize the (Wigand) effect, and so on.

It is utterly impossible to deal exhaustively here with all of the above elements. In this article I will present a summary of elements among the magnetism-detection elements that have been reported up to now which are made of single-crystal silicon, and several integrated magnetic sensors which use these; finally, I will state my personal opinion regarding future silicon magnetic sensors.

2. Silicon Magnetic Sensors

Magnetic sensors that use silicon as their raw material have the advantages that the characteristics of their raw material (silicon) and its manufacturing and processing technologies have been researched deeply, and that it is possible to manufacture a stable and uniform product at a low price, and, furthermore, have the great merit that they make possible the realization of advanced-function integrated sensors (intelligent sensors) by integrating peripheral circuits on the same chip. Below I will introduce silicon magnetic sensors that were reported in the past, and which have the structure of Hall elements or the structure of transistors.

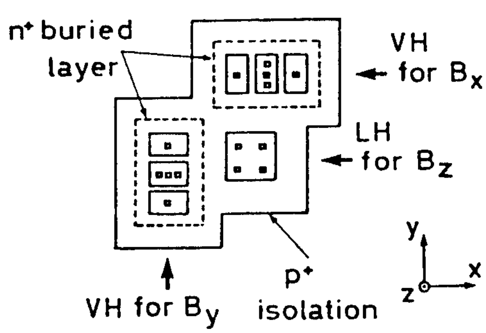

Figure 4. Top View of a Three-Dimensional Magnetic Sensor
LH: Horizontal Hall Element (Corresponding to Figure 1)
VH: Vertical Hall Element (Corresponding to Figure 3)

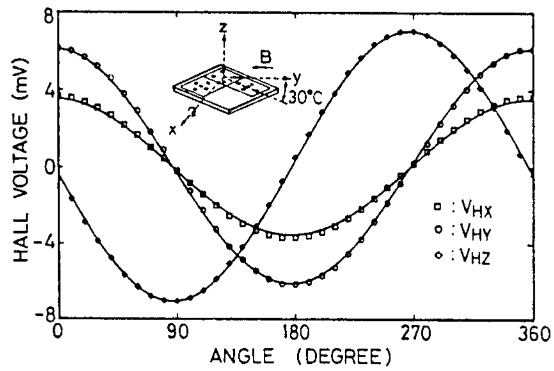

Figure 5. Special Characteristics of Three-Dimensional Magnetic Sensors

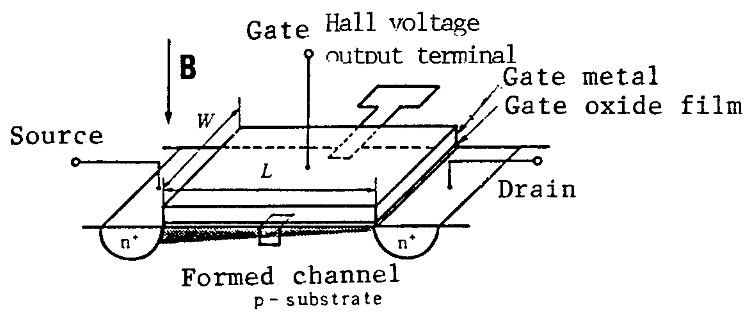

Figure 6. An MOS Hall Element

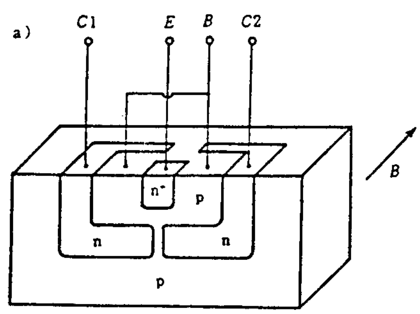

Figure 7. Hudson's Magnetic Transistor

2-1 Hall Elements

Ones which use the silicon's bulk as the active region of the Hall element, and have the structure of Figure 1, which can be realized by the standard bipolar process, have already been put to practical use as the detection part of Hall ICs[1]. In Figure 1 the shape of the Hall

element is determined by p-type separation diffusion, and the current-supply terminal and Hall voltage terminal have been formed in the epitaxial layer of the active region by emitter n^+ diffusion. Since the current flows parallel to the surface of the chip, this element detects magnetic fields that are perpendicular to the chip's surface.

An element has been proposed which would detect magnetic fields that are parallel to the chip's surface in order to detect and apply the vector component of the magnetic field. Figure 2 is a vertical Hall element that can be manufactured by standard C-MOS technology[(2)]. The shape of the element is determined by p-well diffusion. The supply-current that flows in from the central electrode is taken out from the two outside electrodes, but since the active region (n-substrate) spreads out deeply at the the lower part of the central electrode, a current component perpendicular to the chip's surface exists over a considerable length. When, magnetic field B (is added) as in the figure, the Hall voltage, which is derived from the current component that is vertical to the surface of the chip, manifests itself at the output terminal. A (sensitivity) of 250-450V/AT has been obtained with this element.

Figure 3 is a bipolar vertical Hall element that was developed for the purpose of producing the same kind of effect as a C-MOS-type vertical Hall element by means of standard bipolar technology[(3)]. In bipolar IC, unlike MOSIC, the thickness of the active region becomes the thickness of the substrate and the pn-separated epitaxial layer, and is thin, several microns to several tens of microns. This element uses a weak-resistance buried layer in order to cause a current to flow perpendicular to the chip surface by means of a thin active layer. Current that flowed in from the central electrode flows along the epitaxial layer perpendicular to the chip's surface, passes through the buried layer, and is taken out from the outside current terminals. The p-diffusion that obstructs the space between the current terminals checks the current component that flows along the epitaxial layer parallel to the chip surface, and also performs the function of enhancing sensitivity. A (sensitivity) of 47V/AT has been obtained with test-manufactured elements.

A three-dimensional magnetic sensor has been reported that detects simultaneously directions x, y and z of a magnetic field by combining the element shown in Figure 1 with two of the element shown in Figure 3[(4)]. Figure 4 shows its top view, and Figure 5 shows an example of the output of detection of magnetic-field components when the element is caused to rotate inside a specific magnetic field. Magnetic-field components can be detected with a maximum error of three percent.

Sensors have also been reported which use, not bulk, but the MOS transistor's channel, as the active region of the Hall element[(5)]. (Figure 6) Compared with that of bulk, the mobility of the electrons and holes in the channel is low, approximately one-half the level; since the

active region (the channel) is thin, 100 angstrom, one can obtain a comparatively high sensitivity of approximately 1000V/AT[6].

2-2 Magnetic Transistors

The concept of an element that gives to a transistor the function of detecting magnetism, that is, the concept of a magnetic transistor, has been in existence for a comparatively long time; therefore, one even comes across a number that are not aware of "integration." However, virtually all the magnetic transistors that have been reported recently are ones that can be realized by a standard IC process.

Figure 7 is a magnetic transistor according to Hudson's idea[7]; it employs the structure of a transistor that has two separated collector regions. When a magnetic field is not being added, the carrier that is injected from the emitter vertically into the surface of the chip reaches the two collectors equally. As shown in the figure, when one adds a magnetic field parallel to the chip's surface, the carrier inclines to one side because of Lorenz's force, so a difference is produced in the current of the two collectors. According to the journal EDN, at V_{BE}=1V, R_L=10k omega, I_E=1. 2mA it showed a sensitivity of 5V/T, and the temperature change was 0.03 percent[8]. Structurally, Hudson's magnetic transistor cannot be manufactured by a standard bipolar process.

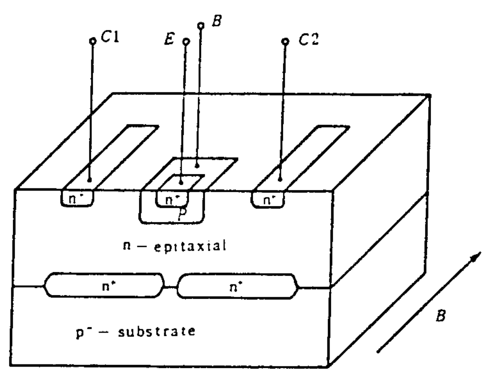

Figure 8. Vertical-Type Magnetic Transistor

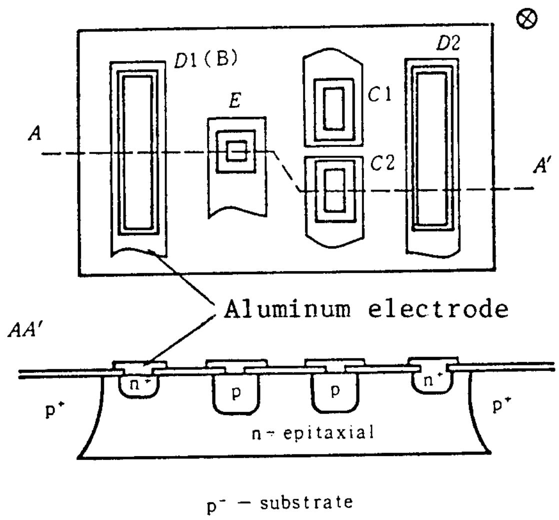

Figure 9. Lateral Magnetic Transistor

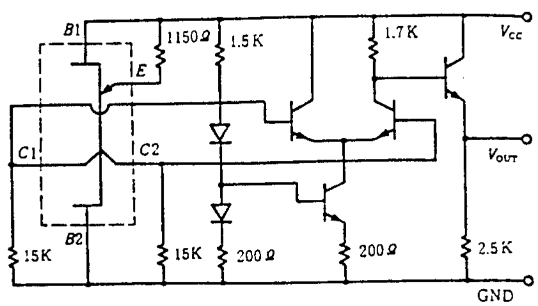

Figure 10. Equivalent-Circuit of an Integrated Magnetic Sensor That Uses a Lateral Magnetic Transistor (The Dotted-Line Part is the Magnetic Transistor)

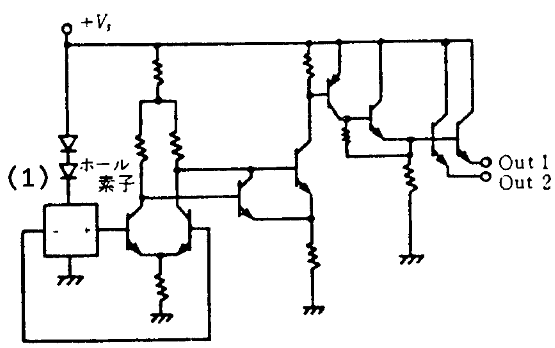

Figure 11. Equivalent-Circuit of the Hall IC Used for the Key Switch

Key:

1. Hall element

Figure 8 is an element that has been improved in such a way that a standard bipolar process can accomodate the structure of Hudson's magnetic transistor[9]. The two collectors are not separated electrically, but it attempts to enhance sensitivity by providing a separated, low-resistance collector buried-layer. Five percent/T is obtained as the comparative sensitivity S (= | delta $I_c/B \cdot I_c$|), in which the collector differential current delta I_c is standardized by all-collector current I_c at the time of (printing) magnetic field B.

Figure 9 is a lateral magnetic transistor that has the structure of a two-collector, lateral transistor[10]. Since the flow of the carrier is mainly parallel to the chip surface, it responds to a magnetic field that is perpendicular to the chip.

In addition, magnetic transistors of really all sorts of structures have been proposed, such as ones with the structure of a two-drain MOSFET[11], ones with the structure of an SCR[12] and ones with the structure of a UJT[13].

3. Integrated Magnetic Sensors

Accompanying the development of magnetism-detection elements that can be manufactured by standard IC processing, it came about that many integrated magnetic sensors were also reported which made the magnetism detection elements and peripheral circuits into monolithic IC. And these reports, too, are advancing along a path of change to higher functions: from things which, in the past, only incorporated amplification circuits, to the incorporation of Schmitt trigger circuits, temperature compensation circuits and motor drive circuits, and also things that use magnetic vectors skillfully and so on.

The circuit shown in Figure 10 is an integrated magnetic sensor that combines a lateral magnetic transistor (figure 9) with a differential amplifier[14], and outputs 10V/T with low impedance.

Figure 11 is a Hall IC circuit that is used for a keyboard's key switch[15]; Figure 1's Hall element, a Schmitt trigger circuit and the output of two emitter-followers have been incorporated. This output method has been considered carefully so as to adapt skillfully to the key matrix that forms the keyboard.

Integrated sensors that possess not only amplifiers and so on, but also functions that perform mathematical processing, have also been reported[16]. As shown in Figure 12, if one incorporates on a monolithic Si chip a magnetic sensor that detects magnetic-field components x, y and z (the one shown in Figure 4), and a circuit that performs the operation

$$B=\sqrt{B_x^2 + B_y^2 + B_z^2}$$

based on the Bx, By and Bz that are output from them, non-directional detection of magnetic fields becomes possible. By this means, real-time measurement becomes possible for magnetic fields of unknown direction, or whose direction changes with time, which, up to now, were difficult to measure with high-precision. The special characteristics of a test-manufactured element that is composed of a total of 161 elements are an error of plus or minus 4 percent, and an imput dynamic range of 34dB[16].

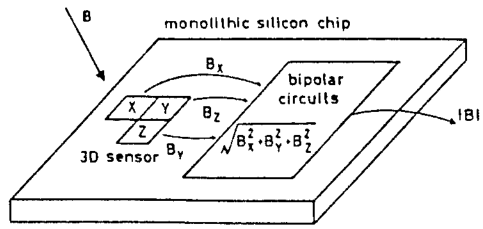

Figure 12. An Integrated Magnetic Sensor That Outputs a Magnetic Field's Absolute Value

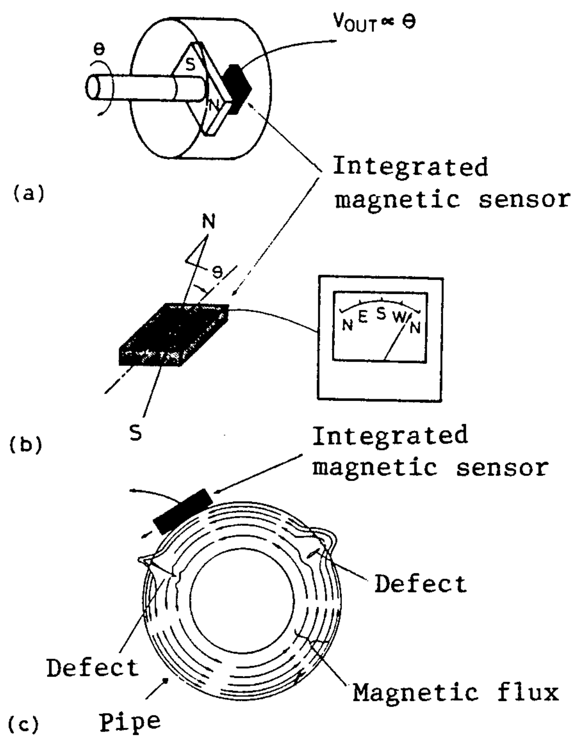

Figure 13. Examples of Applications of Integrated Magnetic Sensors That Output a Magnetic Field's Angle
a: Angle-of-Rotation Detector
b: Bearing Meter
c: Non-destructive Inspection of Steel Pipes and so on

When one combines magnetism-detection elements that detect two-dimensional magnetic-field components Bx and By with a circuit that computes $\Theta = \tan^{-1}(Bx/By)$ based on the components, one is able to realize an integrated magnetic sensor that can detect the direction of two-dimensional magnetic fields[17]. Wide application is conceivable through realization of this kind of integrated magnetic sensor: such things as an angle detector that can detect 360 degrees (The effective detection angle of angle detectors based on conventional MR elements is, at most, 100 degrees.), a bearing meter that can detect terrestrial magnetism, and more precise, non-destructive flaw-detection for steel pipes and so on. (See Figure 13 a, b and c.)

4. The Future of Silicon Magnetic Sensors

As I have shown above, silicon magnetic sensors are in the process of changing their appearance from simplex sensors to high-function sensors that possess computing and processing functions. Now, when high-function control mechanisms are incorporated in all electrical and machine products, sensors should become not only mere physical-quantity conversion devices; they should become parts that give us the quantity that we really desire, or which execute work that we desire. There are reports at present of integrated magnetic sensors that perform comparatively simple signal operations, but I think it is still far from appropriate to call them intelligent sensors. This is strictly my personal opinion, but when the following kinds of sensor, for example, appear, I would want to call them intelligent sensors. 1) An integrated magnetic sensor which, when placed on top of a character written in magnetic ink, would recognize the character inside the sensor, and output the result of the recognition. 2) A magnetic head for data-recording that is also equipped with such functions as code conversion, error checking and error correction. 3) A leakage-magnetic-flux-detecting magnetic sensor for non-destructive flaw-detection, which recognizes the depth, size, shape and so on of the injury, and indicates the measures that should be taken (such as abandonment and reinforcement) and so on.

I end this article with the hope that more and more ideas for making magnetic sensors intelligent will be proposed in the future.

Optical Sensors

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[Article by Norio Koike, Central Laboratory, Hitachi, Ltd.]

[Text] 1. Introduction: Optical sensors are often likened to people's eyes, and it is said that people receive 80 percent of their information from their eyes. Consequently, optical sensors are constituents which are indispensible to information processing, and have grown to the point of being mainstay devices which support the present optical industry. What have played a big role as the driving force of this growth are such things as optical communications, optical disks and video cameras. Furthermore, research on optical sensors is being spurred on greatly by work on optical computers, which began to revive in the 1980's. With this kind of background, many such sensors as simple optical sensors and array-type optical sensors have been developed. Here, focusing on recent optical sensors, and on semiconductor optical sensors in particular, I shall report on the present status of these sensors, and also touch upon future trends.

2. Simple Sensors: When we classify simple optical sensors from the aspects of structure or function, it turns out as in Table 1. Among these sensors, the ones which are being actively researched of late are (1) infrared sensors, which are used mainly for optical communications, and (2) OEIC (optoelectronic integrated circuits), which integrate electronic circuits on optical sensor-substrates.

(1) Infrared Sensors: As shown in Table 2, infrared sensors can be roughly divided into two types: the heat-type and the quantum-type. The heat-type has the thermoelectric type, the bolometer, the pyroelectric type and so on. The pyroelectric infrared sensors listed in the table utilize a phenomenon (the pyroelectric effect) by which, when infrared light strikes a crystal, a temperature change is produced, the magnitude of spontaneous polarization changes in accordance with the

amount of this change, and an electric charge is generated on the crystal surface. Compared with the quantum type, which will be discussed next, the detection sensitivity is low and the response is slow, so research that emphasizes sensitivity and speed is being promoted[1]. The quantum type can be classified into the intrinsic type, which utilizes the crystal's inherent energy gap, and the impurity type, which utilizes the impurity level of added impurities. The former, the intrinsic type, can be divided further into the photoconductive type, in which the degree of electric conductivity changes based on the incidence of infrared light, and the photovoltaic type, in which an electric current is produced by incidence of infrared light. Below, I shall report on a few types of sensors on which R&D has been flourishing of late.

<u>InGaAs Sensors</u>: Ge has been used up to now as an optical diode for use in optical communications on a 1.3-to-1.5-micron wavelength band, but in the last few years development of InGaAs optical diodes that have such special characteristics as a higher quantum effect and a lower dark current has been promoted. In the (---- [abaranshe]-type) (APD) research is being conducted on a structure in which, as shown in Figure 1, separates the (abaranshe-type) multiplying layer from the InGaAs light-absorbing layer, and forms it in the N-In P, and establishes a guard ring at the pn junction part for the purposes of uniform doubling and enhancement of pressure resistance[2]. Attempts to optimize the structure of the (abaranshe) layer are particularly numerous, and recently, high gain-frequency products of 70 GHz have been obtained at low voltages of 50 to 60V by reducing the film-thickness of the n-InP, and raising its concentration (to $7x10^{16}cm^{-3}$)[3,4]. On the other hand, in the PIN-type, development has been carried out which enhances response-speed and sensitivity by attempting to reduce capacity and dark current by lowering the concentration of the light-absorbing layer, reducing the light-receiving path and employing an embedded structure. Through this kind of effort, the speed of the PIN-type is exceeding that of the APD, and its present maximum cut-off frequency has reached 30 GHz[5,6].

Table 1. Classification of Optical Sensors

Structure	Optical diode (PN, PIN, APD) Optical transistor Photo-induction cell
Function	Photo-coupler Photo-interrupter Photo-thyristor Photoelectric switch Light-position-detection sensor Color sensor Optical fiber sensor Optoelectronic integrated circuit Optical functional element

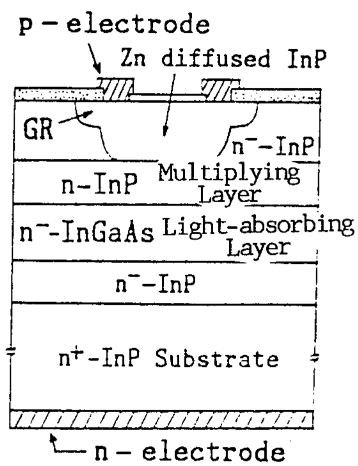

Figure 1. Structure of an APD[2)]

HgCdTe Sensors: Recently infrared fiber with a minimum area loss in the 5 to 10 micron band has been developed. Research is being promoted on $Hg_{1-x}Cd_xTe$ as a long-wavelength band sensor corresponding to this[7,8]. This sensor can change the cut-off frequency freely within the range of 2 to 13 micron by changing the value of x. Consequently, of late such impurity-type sensors as the Ge:Hg and Si:Ga are disappearing because of the advent of this sensor. The sensitivity characteristics of this sensor are shown in Figure 2. Furthermore, research is being conducted of late on infrared image sensors that use HgCdTe as infrared detection material for array-type optical sensors[9].

BPB ($BaPb_{0.7}Bi_{0.3}O_3$)[10]: BPB is a superconductor sensor, and its operating temperature is 4.2K. When infrared light strikes this sensor the photons collide with (Cooper pairs)[kupa tsui], destroy them, and produce quasiparticles. The quasiparticles cause the superconductor energy gap to change, and detect this as a change in the I-V characteristic of a Josephson juncture. Since this sensor's energy gap is small, a few me V, so, as shown in Figure 2, it has highly sensitive detection capacity up to a long-wavelength range, and its speed of response is also fast, 0.1 nanosecond. There is the problem of the operating temperature being 4.2K, but future development is anticipated as a leading sensor in the 2-microns and higher long-wavelength band.

(2) OEIC: OEIC research began to be conducted some 10 years ago based on a different concept from the OIC (optical integrated circuit), which forms photo-conductive paths on a substrate of glass, crystal and so on, and integrates such functions as forking, switching and modulation. The objective of the OEIC is to attempt to improve performance and reduce size and cost by drawing out fully the characteristics of light and electrons, and many such circuits as OEIC photocouplers and rotary encoders have already been developed as products. Recently, research is being promoted in which light-receiving layers and active layers composed mainly of InGaAs are formed on top of substrates of semi-insulating InP, and PIN optical diodes and FET used for amplification are integrated in each layer[11]. The response frequencies of these OEIC are still on a level of a few hundred MHz to 1GHz, so it is low by one decimal place when compared to the previously mentioned simple PIN optical diode. Consequently, research related to enhancement of response speed and sensitivity is currently being promoted; to be precise, such things as shortening of the channel by means of a self-interfacing-type gate structure, reduction of capacity, expansion of Gm and reduction of dark current are being investigated[12].

3. Array-Type Optical Sensors

As shown in Table 3, array-type sensors are divided roughly into one-dimensional image sensors, the light-receiving parts of which are arranged in one dimension, and two-dimensional image sensors, which make mechanical scanning unnecessary by being arranged in two dimensions.

Table 2. Classification and Characteristics of Infrared Sensors

Classification			Material	Wavelength Range (micron)	Operating Temperature (K)	Special Characteristics
Heat Type	Pyroelectric Type		TGS		300	-No wavelength dependence -Cooling unnecessary
			PLZT		300	
			$LiTaO_3$		300	
Quantum Type	Intrinsic Type	Photoinduction Type	PbS	1 ~ 3	300	High sensitivity ($D^* \approx 10^8 \sim 10^{12}$ $cm \cdot Hz^{\frac{1}{2}}/W$) High speed ($10^{-4} \sim 10^{-10}$sec)
			PbSe	1 ~ 4.5	300	
			InGaAs	1 ~ 1.6	300	
			HgCdTe	2 ~ 13	77	
		Photovoltaic Type	Ge	0.6 ~ 1.8	300	
			InGaAs	1 ~ 1.6	300	
			InAs	1 ~ 3	77	
			InSb	2 ~ 5	77	
			HgCdTe	2 ~ 13	77	
	Impurity Type		Ge:Au	1 ~ 10	77	
			Ge:Hg	2 ~ 14	4.2	
			Si:Ga	1 ~ 17	4.2	

(1) One-dimensional Image Sensors: These scanners have various uses in such things as facsimile, computer-input scanners and copying machines, and there are the reduction-reading type, which reads the original with the help of lens optical systems, and the contact type, which reads directly without reducing the original. The contact type can be divided into the film-contact method, which forms a single sensor by using such large-area semiconductor films as CdS-Se film and amorphous Si film (a-Si film), and the multi-chip method, which lines up a multiple number of crystal semiconductor chips such as CCD. The contact type, development of which has been greatly promoted over the last 10 years, has the advantage that, compared with the reduction type, design and adjustment of the optical system is easier, so one can attempt to miniaturize it. On the other side of the coin, it has the disadvantage that a great deal of wiring becomes necessary connecting the IC to the drive-IC, which is attached outside, and to the light-receiving part. The kind of contact-type sensor shown in Figure 3 has been developed recently in order to eliminate this point[13)]. This sensor integrates on the same substrate a PIN optical diode and a shift register for scanning, which is composed of a multi-crystal Si thin-film transistor; a maximum scanning speed of up to 2MHz has been obtained. Furthermore, by using an n-type a-Sic:H for the n-layer of the PIN optical diode, it prevents the injection of holes from the Al electrode, and obtains a low dark current (10^{-13} A/mm^2) and a light/dark ratio of 5 digits or greater.

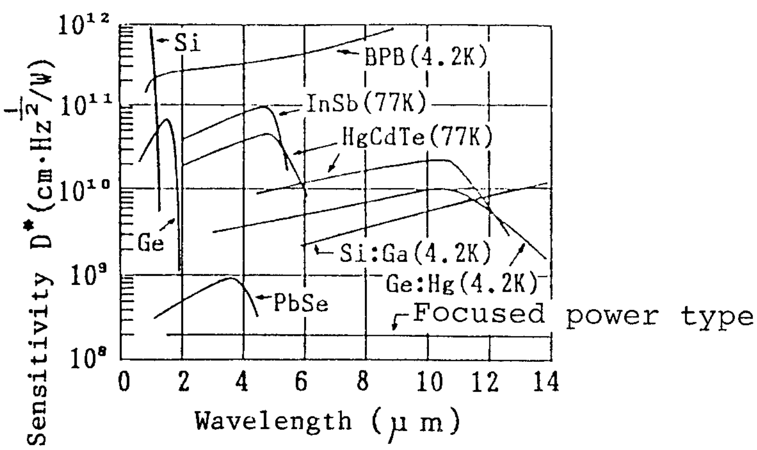

Figure 2. Spectral Sensitivity Characteristics of Infrared Sensors

Table 3. Classification of Array-Type Optical Sensors

One-dimensional image sensors	IC type	MOS scanning method, CCD scanning method
	Contact type	Film-contact method --- photoinduction type, storage type
		multichip method (multiple CCD chips)
Two-dimensional image sensors	MOS type (XY choice)	Conventional method
		TSL method
		CID method
		Amplification method--SIT(*1), CMD(*2), AMI(*3)
	CCD type	Interline transfer method
		Frame transfer method
		Frame interline transfer method
		CSD method (*4), accordion method
	Mixed type	CPD method (*5), RANS method (*6)
	Stacking type	MOS scanning method, CCD scanning method

*1 Abbreviation of Static Induction Transistor
*2 Charge Modulation Device
*3 Amplified MOS Intelligent Imager
*4 Charge Sweep Device
*5 Charge Priming Device
*6 Random Noise SUppression

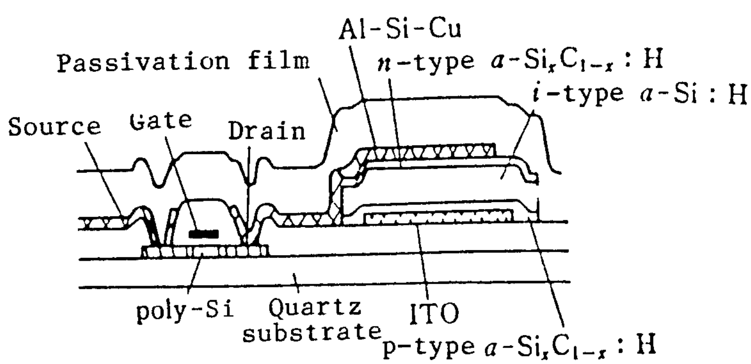

Figure 3. Structure of a Contact-type One-dimensional Image Sensor

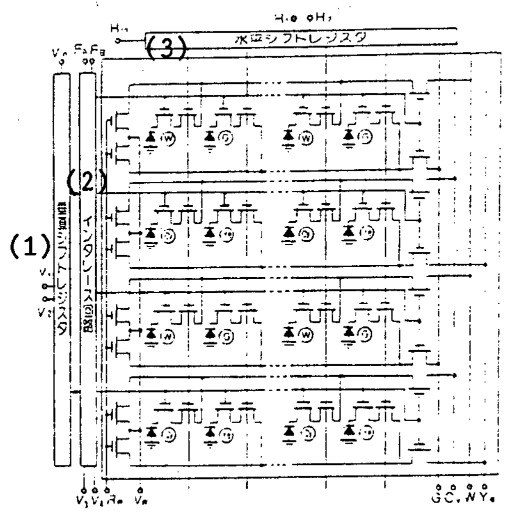

Figure 4. TSL-method MOS Image Sensor[18]

Key:
1. Vertical shift register
2. Interlace circuit
3. Horizontal shift register

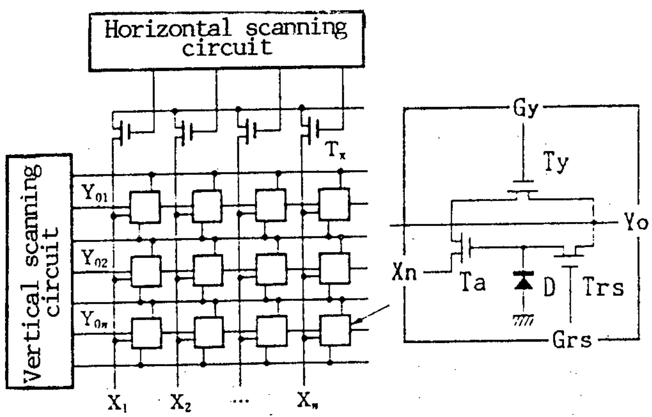

Figure 5. AMI Image Sensor[16]

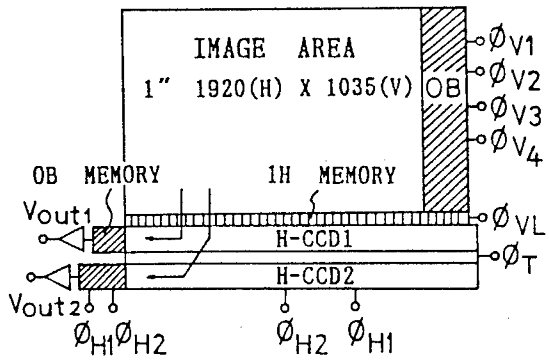

Figure 6. High-definition CCD Image Sensor[24)]

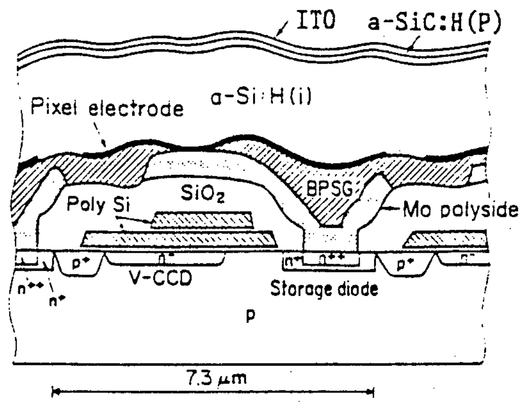

Figure 7. High-definition Stacking-type Image Sensor[25)]

(2) Two-dimensional Image Sensors: Two-dimensional sensors are divided roughly into the XY-choice method, which represents the MOS type, and the CCD type, which transfers signals in one direction. In the last 5 years the performance of the MOS-type sensors and CCD-type sensors carried in the video cameras that are sold on the market has been enhanced to approximately five-fold in regard to sensitivity and two-fold in regard to resolution, so it has become possible to take pictures in a low luminous intensity of 10 lux. Moreover, types of sensor structure and method have also increased, and sensors that amplify signals within such picture elements as SIT[14)], CMD[15)] and AMI[16)] have begun to appear. Below I will report on a few types of two-dimensional sensors that are much talked about of late.

<u>TSL-Method</u> <u>MOS</u> <u>Image</u> <u>Sensors</u>[17,18)]: As shown in Figure 4, this sensor changed the signal-output line of conventional MOS-type sensors from vertical to horizontal, and two switches, vertical and horizontal, are linked to the optical diode. By changing to this kind of structure:

(1) The (smear) storage time is shortened from the former time for one horizontal scan (63.5 microseconds) to the time for one picture-element scan, so the (smear) suppression ratio is enhanced by approximately 50 dB. (2) Since the vertical signal line has disappeared, the parasitic capacity decreased, so it is possible to reduce the volume of noise produced to approximately one-half. Furthermore, because of the NPN structure, which forms N-type optical diodes in P-type wells established on N-type substrates, one can control blooming, control unnecessary infrared sensitivity in visible-light photography, and prevent deterioration of resolution because of diffusion of the electric charge that is generated by long-wavelength light[19)]. This sensor's other special characteristics are low-voltage drive (5V), variegated functions (1/60 to 1/15750 electron shutter and so on) and high sensitivity, and at present many types have been developed as products, such as a 570 (horizontal) x 485 (vertical) sensor and a 760 x 485 sensor.

Amplification-type Image Sensors: When the change in sensors to a greater number of picture elements progresses, it will bring about such things as a decrease in the aperture ratio and an increase in noise accompanying expansion of the signal band. It is hoped that each picture element will be given an amplification function as a measure to relieve this decline in sensitivity. Recently research is being promoted on AMI sensors[16], which inside picture elements amplify in the manner of a circuit and SIT sensors[14)] and CMD sensors[15)], which obtain a large signal current by modulating the height of the electric-potential barrier by means of the charge produced as a result of incident light. Moreover, research is also being conducted on using an APD for the light-receiving part[20)]. The structure of AMI sensors is shown in Figure 5. One picture element is composed of an amplification transistor (Ta), which detects the optical diode's electric potential, a reset-transistor (Trs), which, after detection of the signal, returns the optical diode's potential to what it had been, and a vertical transistor (Ty), which opens and closes by means of a vertical scanning circuit. At present, research is being promoted mainly on reducing the fixed-pattern noise produced by such things as process dispersion when manufacturing the sensors.

High-definition (HD) Image Sensors: It is anticipated that HD sensors will have a wide range of uses in such consumer and industrial fields as electronic still cameras, printing, publishing, cimema and medical treatment, not to mention accomodation to the high definition television system that will use the communications satellite, BS-3, which is scheduled to be launched in 1990. Beginning with the 2048 x 2048 sensor (low-speed scanning)[21)], which was developed in 1985 for use in observation of heavenly bodies, such sensors as 1289 x 960 sensors (picture-element scanning speed: 48 MHz, 30 frames-per-second)[22)], and 1320 x 1035 sensors (14 MHz, 10 frames-per-second)[23] have been reported as multi-picture-element sensors, but none had attained a level which satisfied HD specifications. This year, two kinds of sensors were

developed that satisfied these specifications. One is a 1920 x 1035 sensor[24] composed of the kind of interline CCD that is shown in Figure 6; each stage of the horizontal scanning part is composed of a CCD shift register that operates at 37 MHz (2 stages combined are 74 MHz) and a wide-band, low-noise output amplifier. The photo-sensitivity of this sensor is 67 nA/micoW (wavelength: 550 nm). Another is a 1920 x 1036 stacking-type sensor that formed an a-Si:H layer on top of a CCD scanning substrate as shown in Figure 7.[25] This sensor's photosensitivity is 210 nA/lux, its threshold resolution is 1000 TV lines (horizontal), about the same as that of the CCD image sensor mentioned above, and its after-image is 1.3 percent (the value in the third field).

Other Image Sensors: In addition to those mentioned above, all sorts of sensors have been developed with the aim of enhancing performance and applications. For example, such things as an interline CCD image sensor[26], which attempts to improve color-resolution by simultaneous, independent reading of two lines, and an MOS image sensor[27], which attempts to reduce (smear) by using SOI (silicon on insulator) technology and isolating the signal-output line from the substrate. With the objectives of medical treatment, crime prevention and probing for resources, sensors have also been developed to deal with areas other than visible light. For example, research has been carried out on such things as a 3-to-5-micron-band CCD sensor, the light-receiving part of which is composed of 512 x 512 Pt/Si Schottky-barrier diodes[28], a 3-to-5-micron band CCD sensor in which a 64 x 64 HgCdTe photovoltaic force array is fitted on top of a CCD scanning substrate[29] [misprint], research on applying CCD sensors to the detection of ultraviolet light and X-rays, and research on deep depleted CCD sensors that increase the thickness of depletion layers to several tens of microns in order to increase the quantum efficiency in regard to high-energy X-rays.

4. Future Trends: It is said that people's eyes are composed of vision cells 1 to several microns in size, and that when we convert this to the number of picture elements it is several hundred million. Present-day image-sensors have barely reached several million picture elements, so they do not yet equal people's eyes. However, as stated above, optical sensors possess capabilities which are impossible with people's eyes: they can detect long and short wavelength light other than visible light, their response speed is fast, and so on. It is vital that, while putting these capabilities to use, we go on promoting enhancement of functions and special qualities, the search for physical operations, and development of new materials and manufacturing technology. If, based on the current status of the CCD sensors reported in chapters two and three, I presented the tasks that are anticipated from future R&D, they would probably come out like the following. (1) Development up to now has been based on thinking that gives priority to the physical properties of materials: the idea of "making sensors by making the best use of the inherent qualities possessed by the material." Recently,

contrary to the idea described above, thinking that gives priority to specifications has begun to sprout: the idea of "We want to make this kind of sensor. What kind of material should we use, and how should we design it in order to do that?" In order to realize this kind of idea and go on anticipating new structures and functions, it will be necessary to develop a two-dimensional or three-dimensional method of numerical analysis that will accurately simulate optical devices (optical device CAD). (2) Recently research has begun which tries to use for optical sensors such new materials as organic high polymers that possess photochemical reactions (azobenzene, spiropyrane etc.), biopolymers that possess a photoelectric conversion function (bacteriorhodopsin etc.). Organic materials have problems: on the point of time, their response is still slow, they lack stability for repeated use, and so on, but they have the advantage of being light, and hence suited to an increase in area, so it is predicted that they will develop into attractive materials. (3) The latest research on OEIC is on a trend which points to optical communications and optical computers. In order to go on applying them to these fields, it will be necessary to go on attempting to expand the scale of integration, enhance photosensitivity, develop super high-speed, and so on. Moreover, though I did not mention it in this article, in order to go on developing optical computers and so on, research on optical modulation elements and optical logic elements will begin to be important in addition to development of the kind of performance and materials mentioned above. (4) In regard to image sensors, enhancement of sensitivity, development of higher resolution and development of functions will probably become the nucleus of future development. In order to do this, it will be necessary to develop hyperfine-processing technology that includes a method of picture-element separation, a method of low-noise signal-detection, and proposals for new device composition and structure that will do away with the status quo. The future of a three-dimensional image sensor that was proposed as one plan for this new device structure [29] will attract attention as a method that realizes increased density and development of intelligence sinultaneously. When we look back on the trends that have been described above, we can anticipate that optical sensors will become more and more important as we enter the age of optical information processing which is about to arrive, and that it will go on developing into a key device that will support the society of the 1990's.

In closing, I should like to thank Kazuhiro Ito, Hideaki Yamamoto, Toshihisa Tsukada and Shin'ya Oba of this laboratory, (Iyao) Takemoto of Hitachi's Shigehara plant and Shusaku Nagahara of Hitachi Electronics from whom I received helpful advice when reporting this article.

[footnotes not translated]

- END -

10

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